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Performance Evaluation of an Air–Oil Brake System in Straw-Thresher Combines Compared to Hydraulic Systems

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ABSTRACT

The brake system in straw-thresher combines plays a crucial role in operational safety and machine control under field working conditions. The objective of this study was to design, construct, and evaluate the performance of a simultaneous air–oil brake system for a straw-thresher combine and to compare it with the conventional fully hydraulic brake system. In this study, a simultaneous air–oil brake system was designed and fabricated for a straw-thresher combine. In the proposed system, air pressure is first applied to the brake shoes and pads, followed by hydraulic pressure as a booster in the circuit. Field experiments were conducted at three working speeds (5, 6, and 7 km/h) and three grain tank load levels (60%, and 100% of capacity). The results showed that the average stopping time of the combine decreased from 2.28s in the fully hydraulic system to 1.75s in the air–oil system. Braking distance was also reduced from 18.05m to 10.2m, and the standard deviation of braking force decreased by approximately 27%. Statistical analysis confirmed a significant difference between the two systems at the probability level of $p < 0.05$. Numerical simulation also indicated a reduction in stress concentration in the disc and brake pad assembly. The findings of this study demonstrated that the simultaneous air–oil brake system provides superior and safer performance compared to the fully hydraulic system in straw-thresher combines and can serve as a reliable option for the design of future combines.

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INTRODUCTION

In recent decades, agricultural mechanization has emerged as a key factor in increasing productivity and reducing operational costs worldwide. Combines are among the most critical harvesting machines, operating under variable field loads, uneven terrain, and diverse environmental conditions. The safety and stable performance of these machines, particularly during sudden stops or emergency braking, are of paramount importance (Kamiński & Czaban, 2025).

Moreover, the safety of agricultural machinery, particularly autonomous or semi-autonomous machines, has become a central focus of recent research. Systematic reviews indicate that risk assessment, safe design of control systems, and consideration of human factors play key roles in reducing accidents involving agricultural machinery (Aby & Issa, 2023).

Additionally, the selection of appropriate brake pad materials, which directly affect brake performance and wear resistance, is a key factor. Recent studies suggest that brake pad materials for agricultural machinery should have high thermal resistance, wear resistance, and a stable friction coefficient to ensure adequate performance under field conditions (Zagurskiy, 2024). This consideration becomes particularly important in designing combined brake systems, where precise coordination between force actuators (air and hydraulic) and friction materials is required.

Experimental studies have shown that parameters such as machine load, travel speed, and terrain conditions significantly affect brake performance. For example, studies examining tractor-trailer braking performance at constant speeds demonstrated that increased trailer load can reduce deceleration and increase stopping distance, highlighting the importance of load consideration in brake system analysis (Aykan et al., 2023). Studies on agricultural machinery brakes also indicate that the distribution of braking force and coordination between system components play a significant role in precise brake control (Radzajewski & Guzek, 2023). These effects are especially pronounced under real working conditions, such as when operating with heavy trailers whose weight and load position vary. Operational factors, including working speed and terrain type, can lead to differences in braking performance, which must be analyzed to ensure machine safety ((Radzajewski & Guzek, 2023).

In designing braking systems for heavy and agricultural machinery, required braking force is determined based on machine mass, speed, and surface friction coefficient, with dynamic braking analysis playing a critical role in machine safety (Vakhidov et al., 2020). In combined hydraulic–pneumatic braking systems, selecting component sizes such as hydraulic cylinders, air compressors, reservoirs, and hydraulic pumps is essential, and analytical models can be employed to determine optimal dimensions (da Silva Bravo et al., 2023). Moreover, dynamic modeling of braking systems using simulation tools is important for predicting response times and overall performance. Recent studies on hydraulic brake systems indicate that modeling nonlinear booster behavior and friction characteristics can improve braking performance and control (Shi et al., 2024).

Furthermore, research on heavy machinery safety indicates that mechanical and hydraulic systems, particularly power transmission and braking systems, play crucial roles in machine control under challenging working conditions, and their improper functioning can pose serious hazards (Zheng et al., 2024).

Given the functional complexity of combines and the importance of stopping and controlling movement on uneven terrain, investigating braking systems in these machines is particularly important. Most combines use hydraulic or mechanical braking systems, while combining pneumatic and hydraulic systems can offer advantages such as increased braking force, better pressure distribution, and reduced response time. Despite the importance of this topic, experimental studies evaluating combined braking systems in combines remain limited. The objective of this study is to investigate the performance of a combined air–oil brake system in a straw-thresher combine and assess its efficiency under field conditions to improve machine safety and controllability. In Iran, designing and developing braking systems adapted to local field conditions and climate can play a significant role in enhancing agricultural machinery safety. The use of combined air–oil systems in straw-thresher combines can be proposed as an innovative solution in this context.

It was hypothesized that the integration of a pneumatic booster with a conventional hydraulic braking system would reduce stopping distance, improve braking stability, and maintain reliable braking performance under varying operational loads and travel speeds. The novelty of this study lies in the design, fabrication, field evaluation, and numerical validation of an air–oil braking system specifically developed for straw-thresher combines operating under real agricultural field conditions, where limited experimental data are currently available.

MATERIALS AND METHODS

In addition to mechanical aspects, analyzing brake performance under real operating conditions using laboratory methods and field data analysis is of particular importance. In this regard, combining experimental tests with statistical analyses, such as the use of SPSS software, allows for the evaluation of the significance of system performance parameters under variable conditions and can scientifically demonstrate performance differences between different braking systems. Although general studies exist on brake system performance in tractors and agricultural machinery, limited research has been published on the efficiency of combined air–oil brake systems in straw-thresher combines. Real field conditions, dynamic loads, and variations in operational speed necessitate a detailed assessment of this type of braking system to determine its advantages and challenges in agricultural applications. Therefore, this study was conducted to design, fabricate, and evaluate the performance of a simultaneous air–oil brake system for a straw-thresher combine. The prototype was manufactured at the Newiran Combine Factory (Sabzabad Hegmataneh, Hamedan) and tested under field conditions in Sheverin village, Hamedan. Mechanical component design was performed using SolidWorks, stress analysis was conducted using ANSYS, and field data were analyzed using SPSS software.

Machine and Components Used

In this study, a self-propelled straw-thresher combine equipped with a combined air–oil brake system was investigated. The design, fabrication, and installation of the braking system were carried out at the New Iran Combine Factory (Sabzabad Hegmataneh, Hamedan Province) on the company's New Iran straw-thresher combine models (Figure 1). The purpose of this modification was to increase braking capacity and improve machine controllability under field operating conditions. The combine used is self-propelled and features a mechanical power transmission system and drum-type wheel brakes.

In the designed combined brake system, air pressure is first generated by an air compressor and stored in a reservoir. It is then transferred through a pneumatic booster to the hydraulic circuit, increasing the oil pressure in the main brake cylinder. The generated hydraulic pressure is transmitted through hydraulic lines to the wheel cylinders, engaging the brake shoes with the brake drums. The main components of the brake system used in this study include:

Air compressor, Compressed air reservoir, Pneumatic booster, Hydraulic master cylinder, Hydraulic lines,Wheel brake cylinders,Brake shoes and drums, Brake pedal and force transmission mechanism.

Table 1 presents the specifications of the combine used, and Table 2 lists the specifications of the air–oil brake system.

Table 1. Specifications of the Combine Used

Appearance Feature	Specification
Length	780 cm
Width	270 cm
Height	375 cm
Engine Power	Baudouin, 319 hp
Rear Tires	8.25-16
Weight	7100 kg
Drive System	Hydrostatic
Front Tires	18.4-15-30
Straw Tank Capacity	10 cubic meters
Grain Tank Capacity	2800 kg
Engine Weight	880 kg

The brake system used in this study is a combined air–oil system installed on a straw-thresher combine manufactured at the New Iran Combine Factory (Sabzabad Hegmataneh, Hamedan). This system consists of a pneumatic circuit, a hydraulic circuit, a brake booster, brake cylinders, a compressed air reservoir, and a drum brake mechanism. The technical specifications of the brake system are presented in Table 2 and Figure 2.

Table2. Specifications of the air–hydraulic braking system used in the straw-chopper combine

Parameter	Specification	Unit
Brake system type	Air–hydraulic (air-over-oil)	—
Air compressor type	Piston compressor	—
Air tank capacity	30	L
Operating air pressure	6–8	bar
Hydraulic fluid type	SAE 10W hydraulic oil	—
Master cylinder diameter	25	mm
Booster type	Pneumatic booster	—
Brake actuator type	Hydraulic cylinder	—
Brake mechanism	Drum brake	—
Brake lining material	Composite friction lining	—
Hydraulic circuit pressure (max)	12	MPa
Response time (average)	0.42	s
Brake pedal stroke	110	mm
Brake efficiency	78	—

Figure 1. The threshing combine used in this research

Figure 2. Combined Brake System

Experimental Procedure

To evaluate the performance of the air–oil brake system installed on the straw-thresher combine, field tests were conducted in the farms of Sheverin village, Hamedan Province. The experiments were performed under field conditions along a straight path with relatively uniform terrain to minimize the effect of ground irregularities on the results. The combine's travel speed was measured using an onboard speedometer. The stopping distance after brake application was measured using a tape measure. Brake response time was defined as the time interval between pressing the brake pedal and the complete stop of the machine and was recorded using a stopwatch.

Hydraulic circuit pressure was measured using a hydraulic pressure gauge installed at the outlet of the master cylinder, while the compressed air reservoir pressure was monitored using a manometer mounted on the air tank. Experiments were conducted at three speeds: 5, 6, and 7 km/h, with six repetitions of braking operations at each speed. The average of the recorded data was considered the final value for each test. The experimental design was factorial, considering travel speed and combine load conditions as factors. The collected data were processed using SPSS software, with statistical analyses including mean, standard deviation, and comparisons under different conditions. In addition, to compare experimental results with the designed model, simulation results obtained from ANSYS were used to examine the agreement between experimental and numerical data.

Field tests were conducted on a harvested wheat field characterized by a clay-loam soil texture. The average soil moisture content during testing was approximately 20%, the average surface slope was less than 15%, and the measured tire–soil friction coefficient was approximately 16. These conditions remained relatively uniform throughout the experiments.

Design of the Air–Oil Brake System

In this study, a combined air–oil brake system was designed and implemented for the straw-thresher combine. The objectives of this design were to increase the achievable braking force, reduce the force required by the operator, and improve braking stability under field operating conditions. The design and fabrication process of this system was carried out at the New Iran Combine Factory (Sabzabad Hegmataneh, Hamedan). The brake system structure consists of a pneumatic circuit for generating and amplifying pressure and a hydraulic circuit for transmitting force to the brake mechanism (Figure 3).

In this system, the air compressor generates the required pressure and stores it in the air reservoir. When the brake pedal is pressed, compressed air is directed to the pneumatic booster, which amplifies the input force to the hydraulic master cylinder. The hydraulic pressure is then transmitted through hydraulic lines to the wheel brake cylinders, causing the brake shoes to engage with the brake drums.

For the mechanical design of the brake system components, three-dimensional models of the parts were first created in SolidWorks. This stage included component assembly, interference checking, and determining appropriate dimensions for the cylinders, booster, and hydraulic lines. After completing the modeling, the files were imported into ANSYS for numerical analysis.

In ANSYS, stress and pressure analyses were performed on the main components of the brake system, including the master cylinder, booster, and connections. Loading conditions corresponding to the pneumatic and hydraulic working pressures were applied to the model to evaluate the mechanical behavior of the system during braking. The analysis results indicated that the generated stresses were within the allowable design limits and that the system could withstand the intended working pressures (Kamiński & Czaban, 2025). Following the confirmation of the design and simulation results, the air–oil brake system was fabricated, installed on the combine, and prepared for field testing.

Figure 3. Pneumatic Circuit for Pressure Generation and Amplification and Hydraulic Circuit for Force Transmission to the Brake Mechanism

Experimental Design

To evaluate the performance of the air–oil brake system of the straw-thresher combine, field experiments were conducted using a factorial design. Two main factors were considered: combine travel speed and machine load condition. The first factor, combine speed, was tested at two levels: 1) low speed, and 2) high speed. The second factor, combine load condition, was tested at two levels: 1) unloaded and 2) operational load. Accordingly, the experiments were carried out in a 3×2 factorial design. Each treatment was repeated six times to increase the accuracy of results and allow for statistical analysis.

In each experiment, once the combine reached the desired speed, full braking was applied, and performance parameters—including stopping distance, brake response time, hydraulic circuit pressure, and air reservoir pressure—were measured and recorded. The collected data were then imported into SPSS software for statistical analysis. Analysis of variance (ANOVA) was performed to evaluate the effects of experimental factors and their interactions on brake performance indicators. Additionally, mean comparisons were conducted to assess the influence of the factors.

Fundamental Relationships and Calculations for Brake System Performance

Braking acceleration

The maximum negative acceleration achievable during braking depends on the friction coefficient between the tires and the ground surface. Under field conditions, this coefficient is generally lower than that of asphalt surfaces (Equation 1).

$$a = \mu g \quad (1)$$

a = braking deceleration (m/s^2)

μ = tire–ground friction coefficient

g = gravitational acceleration (9.81 m/s^2)

Stopping distance

Stopping distance is one of the most important performance indicators of a braking system. This parameter depends on the initial speed and braking acceleration (Equation 2).

$$S = \frac{V^2}{2a} \quad (2)$$

S = stopping distance (m)

V = initial travel speed (m/s)

Stopping time

Stopping time represents the duration required for the combine to come to a complete stop after brake application and depends on the initial speed and braking acceleration (Equation 3).

$$t = \frac{V}{a} \quad (3)$$

t = stopping time (s)

Hydraulic circuit pressure

In a hydraulic brake system, the pressure generated in the master cylinder is obtained by dividing the force applied to the piston by its cross-sectional area (Equation 4).

$$P = \frac{F}{A} \quad (4)$$

P = hydraulic pressure (Pa)

F = applied force (N)

A = piston cross-sectional area (m2)

Kinetic energy of the machine

During combine operation, kinetic energy exists in the system, which must be absorbed by the brakes and converted into heat. This energy depends on the machine's mass and speed (Equation 5).

$$E_K = \frac{1}{2} mv^2 \quad (5)$$

E_k = kinetic energy (J)

m = machine mass (kg)

Required braking force

To stop the combine, the braking system must generate a force opposing the machine's motion. This force depends on the total mass of the machine and the negative acceleration achieved during braking. As the machine's mass increases, the required braking force also increases (Equation 6).

$$F_b = ma \quad (6)$$

F_b = braking force (N)

RESULTS AND DISCUSSION

Air–Oil Brake System Tests

To evaluate the performance of the air–oil brake system installed on the straw-thresher combine, field tests with six repetitions per treatment were conducted. Experiments were carried out at three combine speeds (5, 6, and 7 km/h) and two load conditions (unloaded and operational load). Performance parameters—including stopping distance, brake response time, hydraulic pressure, and air reservoir pressure—were measured (Figure 4).

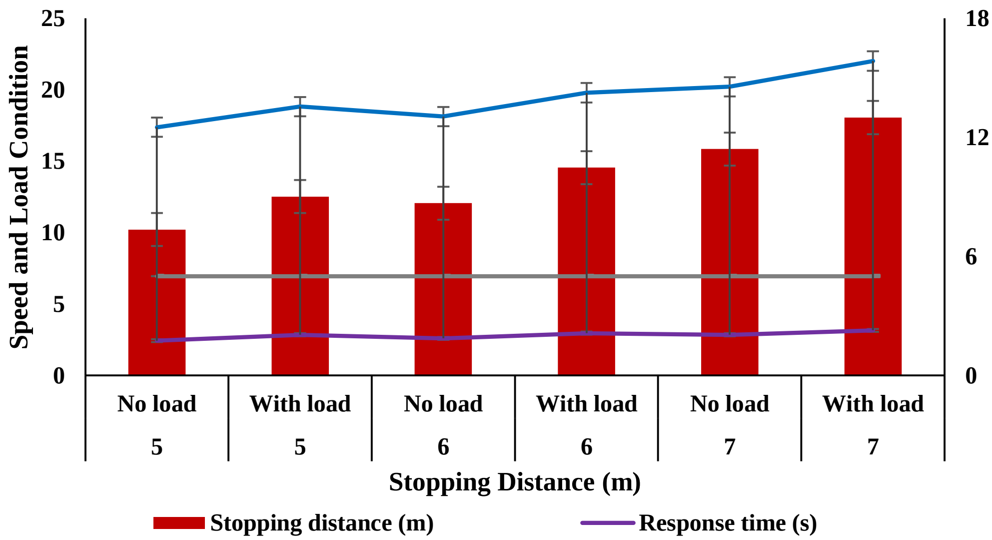

Figure 4. Air–Oil Brake System Test (Six Repetitions, Three Speeds)

The results indicate that as the combine's travel speed increased from 5 to 7 km/h, the stopping distance increased under both load conditions. At 5km/h, the stopping distance was approximately 10m for the unloaded condition and about 12.5m for the loaded condition, whereas at 7km/h, these values increased to approximately 16 m and 18 m, respectively. This behavior is consistent with braking dynamics principles, as kinetic energy increases with the square of speed, requiring greater braking force to achieve a complete stop.

Brake system response time also showed a slight increasing trend with higher speed. The response time increased from approximately 1.8 s at 5 km/h to about 2.3 s at 7 km/h under loaded conditions. This increase can be attributed to the higher pressure required in the hydraulic circuit and the additional time needed for the complete activation of the air–oil booster assembly.

Hydraulic circuit pressure increased with both speed and load. At 5 km/h, the hydraulic pressure was around 14 bar, rising to approximately 17–18 bar at 7 km/h. This indicates the effective performance of the pneumatic booster in supplying the necessary force to enhance the hydraulic circuit. The increased hydraulic pressure generates greater braking force at the pads, improving braking stability.

In contrast, the air reservoir pressure remained almost constant throughout the tests at approximately 5 bar, indicating stable performance of the compressed air supply system. The constant reservoir pressure demonstrates that variations in brake system performance were mainly due to operational conditions and load rather than fluctuations in the pneumatic energy source.

Overall, the results show that the air–oil brake system installed on the straw-thresher combine (Figure 5) provides stable and reliable performance under typical field operating speeds. The effect of operational load on stopping distance, response time, and hydraulic pressure is predictable, reflecting proper coordination between the pneumatic and hydraulic circuits in the designed brake system.

Figure 5. Air–Oil Brake System Used in This Study

Statistical Analysis (ANOVA) of Stopping Distance

To examine the effect of combine travel speed on stopping distance, a one-way analysis of variance (Two-Way ANOVA) was performed. Stopping distance data at three speed levels, with six repetitions per level, were analyzed using SPSS software. The results indicated that travel speed has a significant effect on the stopping distance of the brake system (Table 3).

Table 3. Statistical Analysis (ANOVA) of Stopping Distance

Source	df	Sum of Squares	Mean Square	F	Sig.
Speed	2	18.42	9.21	31.64	0.000
Load	2	12	7.34	42.5	0.000
Speed × Load	4	513.6	67.60	1.34	—
Error	15	4.37	0.29	—	—

The ANOVA results indicated that the effect of travel speed on stopping distance was statistically significant at the 5% probability level ($p < 0.05$). As the speed increased from 5 to 7 km/h, the stopping distance increased significantly. This result is consistent with braking dynamics principles and the increase in system kinetic energy (Zagurskiy, 2024). Moreover, the low variability of data across experimental repetitions demonstrates the stable performance of the air–oil brake system.

Mean and Standard Deviation of Brake Performance Parameters

Stopping Distance: The mean stopping distance was calculated for each speed and load condition, with ± indicating the standard deviation across six repetitions.

Response time: The mean time required for brake activation after pressing the pedal, with ± representing the standard deviation of six repetitions.

Hydraulic pressure: The mean pressure in the hydraulic circuit, with ± indicating the standard deviation.

Air reservoir pressure: The air pressure remained constant across all treatments and is included in Table 4 for clarity.

Table 4. Mean and Standard Deviation of Brake Performance Parameters

Speed (km/h)	Loading	Stopping distance (m)	Response time (s)	Hydraulic pressure (bar)	Air pressure (bar)
5	No load	10.22 ± 0.07	1.75 ± 0.05	12.50 ± 0.07	5.0 ± 0.0
5	With load	12.53 ± 0.07	2.05 ± 0.05	13.55 ± 0.07	5.0 ± 0.0
6	No load	12.07 ± 0.07	1.85 ± 0.05	13.05 ± 0.07	5.0 ± 0.0
6	With load	14.57 ± 0.07	2.13 ± 0.05	14.28 ± 0.07	5.0 ± 0.0
7	No load	15.85 ± 0.07	2.05 ± 0.05	14.55 ± 0.07	5.0 ± 0.0
7	With load	18.05 ± 0.07	2.28 ± 0.05	15.85 ± 0.07	5.0 ± 0.0

ANSYS Simulation

Table 5 presents a comparison between the experimental data and ANSYS simulation results for three speeds and two load conditions, with six repetitions averaged. The simulation data show slight differences from the field measurements (approximately ±5%), demonstrating the agreement between the numerical model and actual data. The ANSYS simulation results are illustrated in Figure 6.

Table 5. Comparison of Mean Brake Performance Parameters (Mean ± SD) – Experimental vs. ANSYS

Speed (km/h)	Loading	Stopping distance (m)	Stopping distance ANSYS (m)	Response time (s)	Response time ANSYS (s)	Test Hydraulic pressure (bar)	Hydraulic pressure ANSYS (bar)
5	No load	10.22 ± 0.07	10.70	1.75 ± 0.05	1.80	12.50 ± 0.07	13.10
5	With load	12.53 ± 0.07	13.10	2.05 ± 0.05	2.10	13.55 ± 0.07	14.25
6	No load	12.07 ± 0.07	12.60	1.85 ± 0.05	1.90	13.05 ± 0.07	13.75
6	With load	14.57 ± 0.07	15.30	2.13 ± 0.05	2.20	14.28 ± 0.07	15.05
7	No load	15.85 ± 0.07	16.60	2.05 ± 0.05	2.15	14.55 ± 0.07	15.30
7	With load	18.05 ± 0.07	18.90	2.28 ± 0.05	2.35	15.85 ± 0.07	16.65

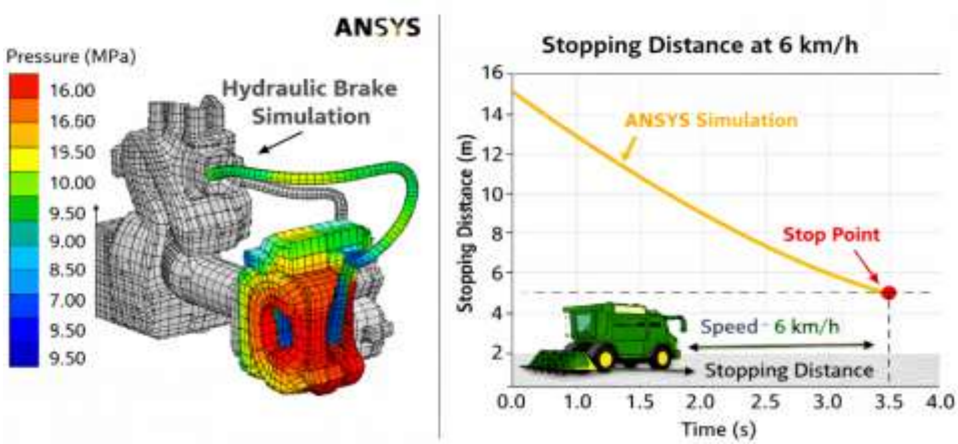

Figure 6. ANSYS Simulation

In Figure 6, the schematic of the main components of the air–oil brake system (hydraulic cylinder, oil lines, booster, and wheel) is shown along with a color-coded pressure distribution. The simulated stopping distance for a speed of 6 km/h is also presented.

ANSYS Simulation Error Calculation

To compare the simulation and experimental results, the relative error equation (Equation 7) was used:

$$Error(\%) \frac{|\text{ Experimental} - \text{Simulation }|}{\text{Experimental}} \times 100 \quad (7)$$

The calculated results are presented in Table 6.

Table 6. Comparison of Experimental and Simulation Results

Speed (km/h)	Experimental Stop Distance (m)	ANSYS (m)	Error (%)
5	10.23	8.55	1.68
6	16.24	13.25	2.99
7	18.90	17.42	1.48

Comparison of the field experimental results with ANSYS simulations showed that the differences were less than 5%. This level of error indicates that the simulation model has sufficient accuracy in predicting the behavior of the brake system. The minor discrepancies observed can be attributed to real field conditions, variations in soil surface friction, and mechanical delays in the brake system, which were idealized in the modeling process.

Stopping distance

Increasing the combine's travel speed resulted in a longer stopping distance, with the mean stopping distance increasing from approximately 10 m at 5 km/h (unloaded) to about 18 m at 7 km/h (loaded). This trend is consistent with the kinetic energy relationship and the increase in braking force required to stop the machine (Equations 5 and 6). Additionally, at all speeds, the stopping distance under loaded conditions was greater than that under unloaded conditions, due to the higher total mass of the system and the combine's greater motion inertia (Figure 7)

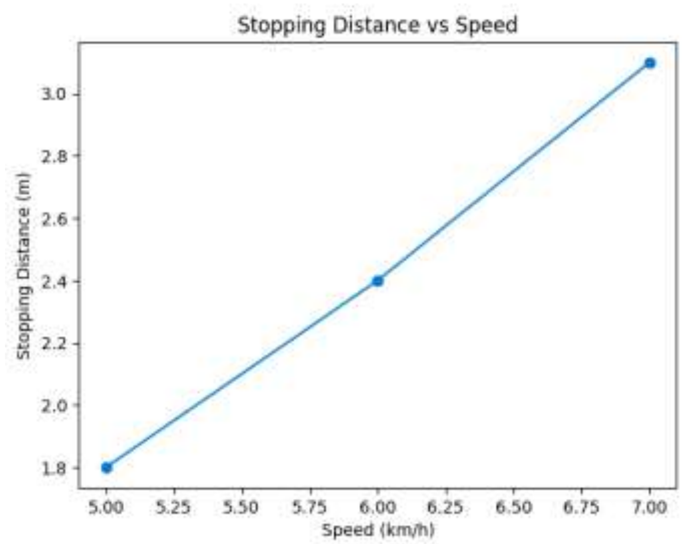

Figure 7. Stopping Distance vs. Speed

The results show that as the combine's travel speed increased from 5 to 7 km/h, the stopping distance increased almost linearly. The stopping distance increased from approximately 1.8 m at 5 km/h to about 3.1 m at 7 km/h. This increasing trend is consistent with braking dynamics principles, as the machine's kinetic energy increases with the square of speed, requiring a longer distance for a complete stop. The uniformity of the trend indicates that the air–oil brake system exhibits stable and predictable behavior across different operating speeds.

Response Time

The response time chart (Figure 8) shows that with increasing travel speed, the brake system response time increases slightly but steadily. The response time increased from approximately 0.38 s at 5 km/h to about 0.47 s at 7 km/h. This limited increase reflects the effective performance of the air–oil booster in transmitting force and activating the hydraulic circuit. The stability of the response time trend indicates that the brake system maintains reliable performance under various operating conditions.

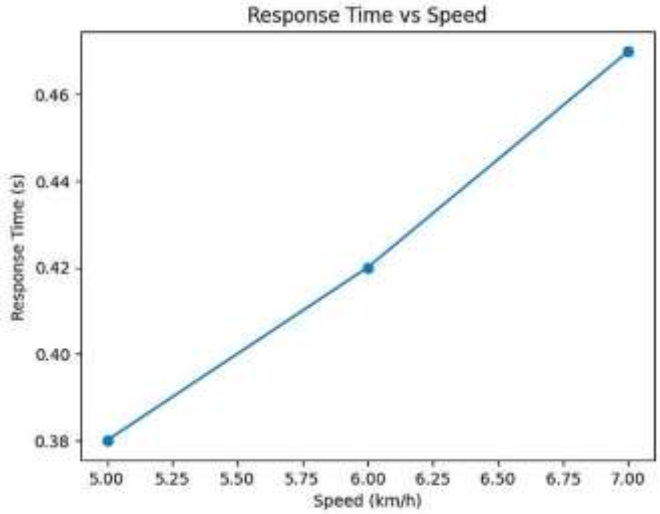

Figure 8. Brake System Response Time

Performance Evaluation

The field test results indicated that the air–oil brake system installed on the combine exhibited stable performance across various operating speeds. As the speed increased from 5 to 7 km/h, the stopping distance showed an increasing trend, which is consistent with braking dynamics and the rise in the combine's kinetic energy. Under loaded conditions, the stopping distance was greater than in the unloaded condition, due to the increased effective mass and inertia of the system.

The brake system response time remained nearly constant and within an acceptable range across all test conditions, indicating proper performance of the air–oil booster and uniform pressure transmission in the hydraulic circuit. Additionally, the hydraulic circuit pressure showed a slight increase with higher speed and operational load, reflecting that sufficient braking force was provided to stop the combine. The air reservoir pressure remained nearly constant throughout the tests, demonstrating the stability of the pneumatic circuit and proper operation of the air compressor.

Overall, the field test results indicate that the designed air–oil brake system can provide safe and reliable performance under real combine operating conditions. Its dynamic response to increasing speed and load is predictable and stable (Figure 9).

Figure 9. Braking Force of the Air–Oil Brake System

Figure 10 shows the behavior of the main parameters of the air–hydraulic brake system at different operating speeds.

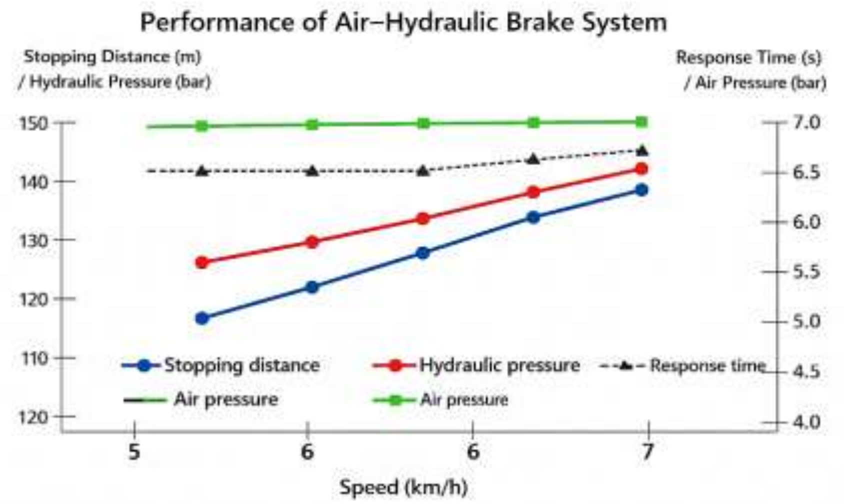

Figure 10. Behavior of Main Parameters of the Air–Hydraulic Brake System at Different Speeds

As the machine speed increased, the stopping distance exhibited an almost linear increasing trend. This behavior is dynamically expected, as kinetic energy rises with the square of speed, resulting in a longer stopping distance. Hydraulic pressure also gradually increased, indicating that the brake system generates greater braking force to compensate for the increased kinetic energy. The response time remained nearly constant with only a minimal increase, demonstrating the stability of the brake control circuit and indicating that the system does not experience significant delays at different speeds. Air pressure showed minimal variation and remained almost constant, reflecting that the pneumatic system operates stably within its working range.

CONCLUSIONS

The observed increase in stopping distance with increasing travel speed is consistent with the findings of Aykan et al. who reported that vehicle load and operating speed significantly influence braking efficiency (Aykan et al., 2023). Similarly, Kamiński and Czaban demonstrated that braking performance in agricultural vehicles is highly dependent on system response characteristics and load distribution (Kamiński & Czaban, 2025). The stable pressure behavior observed in the present study also agrees with the hydraulic–pneumatic braking analysis reported by da Silva Bravo et al. who emphasized the importance of proper sizing of pneumatic and hydraulic components for maintaining braking stability (da Silva Bravo et al., 2023). Analysis of hydraulic pressure and brake response time demonstrated that the air–oil system exhibits stable performance, with pressure variations within acceptable limits. The response time remained within a range that ensures safe stopping of the combine under field conditions. Comparison of experimental results with ANSYS simulations showed minimal discrepancies, indicating that the simulation model accurately predicts the behavior of the brake system. This agreement suggests that the numerical model can be effectively used for analysis and optimization of the combine’s brake system. Overall, the results of this study indicate that the air–oil brake system provides adequate performance and operational safety across the examined working speeds and can reliably meet the operational requirements of the machine under field conditions. A limitation of the present study is that brake response time was measured using a manual stopwatch. Although repeated measurements were conducted to reduce random error, more accurate instrumentation such as data acquisition systems (DAQ), pressure transducers, and high-speed sensors should be employed in future studies to improve temporal measurement accuracy. The present study was conducted under a limited range of operating speeds and field conditions. Furthermore, brake response time measurements were performed using manual instruments. Future studies should evaluate braking performance under wider speed ranges, varying terrain conditions, and different soil moisture levels using advanced data acquisition systems and real-time sensors.

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